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Day Lighting as a Factor in Optimizing the Energy Performance of Buildings

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Theoretical evidence is presented on the possibility that proper window sizing as well as proper selection of external surface to volume ratio can result in total energy savings for heating, cooling and lighting in the periphery zones of buildings. The savings are of the order of 50% relative to the windowless configuration. The optimum window area ranges from 10% to 40% of the wall area depending on the size and geometry of the spaces. The calculations were carried out for Austin, Texas using hourly weather data averaged over a 9 year period. The results of the calculations are strongly dependent on the sky illumination calculations. A model of the sky illumination that calculates the perceived intensity of illumination as a function of weather conditions and the orientation of the receptor relative to the sun is developed and the results of an empirical test run on the model are included.

INTRODUCTION

Artificial illumination is one of the major consumers of energy in commercial and institutional buildings. As such, it is one of the main areas of concentrated study in the efforts to reduce energy consumption in buildings. These efforts range from the re-evaluation of the recommended illumination levels (RQQ committee of the IES) for various activities and the wider adoption of task lighting, to the development of impedance control of lighting fixture ballasts to take advantage of day light intensities, as well as the development of films with selective transmittance for application on windows. Efforts to systematically coordinate day lighting availability with the layout of artificial lighting in order to improve the overall energy performance of buildings has had a slow start. This may be due to the difficulty associated with the calculation of the intensity and contrast of the illumination within buildings, and also due to the complexity of sky-illumination calculations. The latest comprehensive reports on day-lighting are found in books published 10 to 20 years ago (Hopkinson [1], Walsh [2]). More recent data on the intensity and distribution of sky illumination is becoming more available (Nakamura and Oki [3]), as are efforts to integrate the thermal and illumination aspects (Selkowitz and Rosenfeld [4]). Computer algorithms to calculate the intensity and contrast of illumination in a room are of course available on a proprietary basis. Some of these are reported to integrate sky illumination effects (Dave DiLaura LUMEN 2).

This article is a first generation effort of this author to integrate thermal and illumination calculations for the purpose of reducing the overall energy consumption of a building.

The conclusions, which should be considered as tentative, indicate the existence of optimum window areas that render the total annual energy consumption for heating, cooling and lighting to a minimum. The reduction in total energy consumption can be as great as 50% (from 55,000 Btu/ft^2 of floor area to 23,000)* with the appropriate combination of percent window on the wall and surface to volume ratio.

Since the validity of the conclusions is strongly dependent on the reliability of the sky illumination algorithm, the first part of the article is devoted to its description. Preliminary tests comparing the predicted sky illumination with measured values are sufficiently close to encourage further investigation of the approach presented here.

*161 kWh yr^{-1} m^{-2} to 67 kWh yr^{-1} m^{-2}.

Calculation Model

The model developed here to estimate the sky illumination is based on published data. No effort is made to develop its theoretical basis.

The beam or direct component of the radiation can be estimated without difficulty from geometric arguments. There seems to be, however, no satisfactory way to model the diffuse and scattered components, specially to account for variable weather conditions. Where possible, therefore, empirical data should be used. In order to see how some calculations can be carried out from empirical data consult Duffie and Beckman [5], Meinel and Meinel [6], Sellers [7], Gates [8].

The model used here for estimates of direct and diffuse radiation follows from four arguments:

(a) That the direct beam contribution is directly proportional to the direction cosine of the solar ray.

(b) That the atmospheric attenuation (extinction coefficient) of the direct beam can be calculated by Brooks' formula (An Introduction to Physical Microclimatology, Davis 1959) as reported by Gates (p. 52) [8].

(c) That the dependence of diffuse radiation on the extinction coefficient can be obtained from Liu and Jordan's data [6].

(d) That we can separate the direct and diffuse components on a horizontal surface and recombine them with appropriate geometric arguments for surfaces with new orientations.

Argument (c) is perhaps the most suspect because it makes several "liberal" interpretations of reported data.

Liu and Jordan, as reported by Duffie and Beckman [6] (p. 47), reduced the data of daily diffuse, and extraterrestial insolation on a horizontal surface into a single graph (Fig. 1).

$y = d/T \qquad x = T/S$

where d is the diffuse insolation, T the total insolation, and S the extraterrestial insolation.

Given this graph, the argument proceeds as follows:

1. Assume that the results hold for any given instant of time and not only for daily averages.

2. That when the total radiation received is equal to the extraterrestial radiation ($x = 1$), then there is no diffuse radiation. The scattering of the data near this limit may permit the y value to range from zero to 0.2.

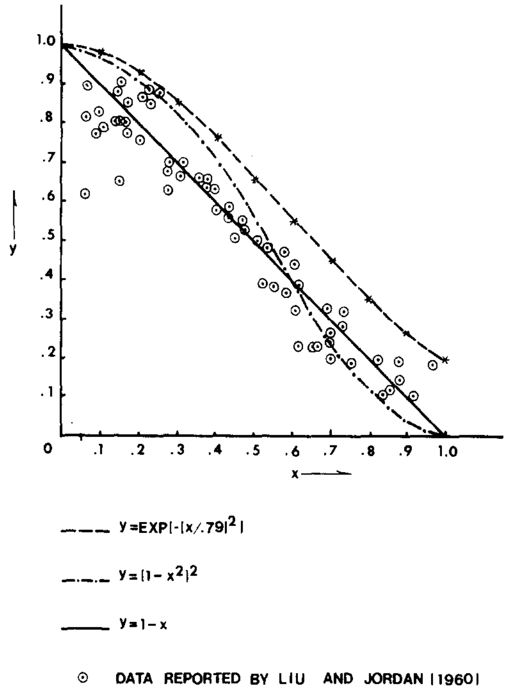

Fig. 1. Data reported by Liu and Jordan relating the diffuse to total radiation ration with the total to the extraterrestial radiation ratio. The curves represent 3 possible fits to the data. The straight line fit is chosen for the model in calculations reported in this article.

3. The data as shown could be fitted approximately with a number of equations

a. $y = \exp\{-(x/0.79)^2\}$ if $y = 0.2$ for $x = 1$

b. $y = (1 - x^2)^2$

c. $y = 1 - x$

Because of the many assumptions built into this argument, the simplest algebraic expression is the one used in the calculations.

4. The total radiation (T) is assumed to mean diffuse plus direct ($T = D + d$) and the direct (D) component is assumed to be given by the product of the extinction coefficient (α) (as given by argument (b)) times the extraterrestial value ($D = \alpha S$).

5. The extraterrestial value (S) is taken to be the value that would be intercepted in the absence of atmosphere. It is given by the product of the solar constant (S_c) times the direction cosine (σ) of the receiving surface. ($S = \sigma S_c$).

From these assumptions, it follows that the diffuse, direct, and total radiation components

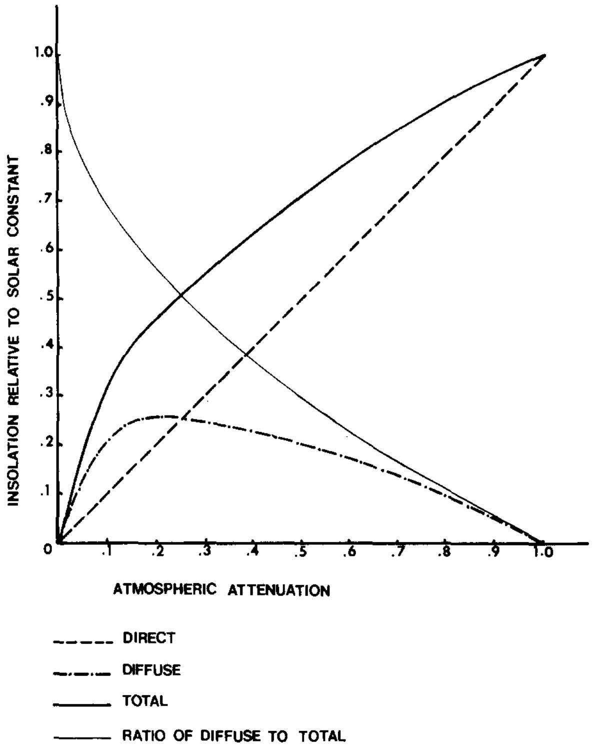

Fig. 2. Insolation measured in units of the solar constant as a function of the atmospheric attenuation factor. The values of the direct, diffuse, and total radiation are shown as they are derived from the Liu and Jordan data following the assumptions of the model.

intercepted by a horizontal surface can be expressed by the equations:

$$d = (\sqrt{\alpha} - \alpha)\sigma_u S_c$$

$$D = \alpha\sigma_u S_c$$

$$T = \sqrt{\alpha}\sigma_u S_c$$

Figure 2 illustrates these values as function of the atmospheric attenuation factor.

The illumination intensity on a surface

The illumination on a surface is given by three terms:

1. The direct illumination component

$$D_c = \sigma_n \alpha S_c O$$

where σ_n is the direction cosine of the sun relative to the vector normal to the surface. For orientations such that $\sigma_n < 0$, the surface is facing away from the sun, and D_c should be set to zero. O is the obstruction factor of the direct beam.

2. The diffuse illumination component

$$d_c = G(\sqrt{\alpha} - \alpha)\sigma_{eff} S_c$$

where G is the view factor of the sky as seen by the surface; and σ_{eff} is the effective direction cosine of the sun relative to the surface's normal direction. The expression for the effective direction cosine is chosen so that it satisfies the observed phenomenon that on the arc of a great circle going through the solar position, the lowest intensity is found about 90° away from the sun. (This phenomenon was explained by Pokrowski [11] as being a Raleigh scattering effect.) The formula used here is $\sigma_{eff} = \{(\sigma_n^2 + \sigma_u^2)/2\}^{1/2}$, and it satisfies both the Pokrowski effect as well as our interpretation of Liu and Jordan's data.

3. The reflected illumination component is made of two parts: the reflection of direct radiation, and the reflection of diffuse radiation. If we assume that the reflected direct beam can be treated as an extended source, then the total reflected term is given by

$$R = \rho G_r \sqrt{\alpha}\sigma_n S_c$$

where ρ is the effective background reflectance, and G_r is the view factor of the reflecting surfaces as seen by the surface.

4. The visible intensity energy flux that corresponds to the solar constant is 120,000 lumens/m^2.

Empirical test

The sky illumination intensity was measured using a Weston Foot-Candle meter model 614. Since the measuring scales do not go high enough to register the outdoor intensities, the photocell was masked. The reduction factor of the mask was 1/16. The measurements were taken on the South Mall of the University of Texas at Austin campus. From the point where the measurements were taken one has a clear view of the southern sky. The east and west skies are partially obstructed by buildings 3 stories high at a distance of about 80 ft. The north sky is partially obstructed by a 30 story tower about 60 ft away.

The estimated view factors along the various orientation are given in Table 1. The measurements were taken on April 5, 1977. The sky was totally clear with no clouds of any type visible at any time during the observations. The sky illumination intensities are reported in Table 2.

TABLE 1

	Estimated sky view factor	Estimated "ground" view factor	Estimated background reflectance
South	0.48	0.52	0.14
East, West	0.42	0.58	0.03
North	0.32	0.68	0.08
Zenith	0.85	0.15	0.05

TABLE 2

Units: foots candles

Time	South	East	North	West	Zenith
10:00	4480 (?)	3520	800	800	4480
11:00	3200	2560	960	800	5920
12:00	3520	1440	960	960	7200
14:30	2480	800	960	4160	6080
15:30	1280	640	720	5920	4560
16:40	800	480	640	6080	3040
17:30	320	320	960	5280	1440

TABLE 3

Direction cosines

Time	South	East	North	West	Zenith	Atmospheric attenuation*
6:00	0	0.99	0.14	0	0.08	0.05
7:00	0	0.95	0	0	0.30	0.20
8:00	0.12	0.85		0	0.51	0.31
9:00	0.22	0.70		0	0.68	0.38
10:00	0.30	0.49		0	0.82	0.42
11:00	0.35	0.26		0	0.90	0.44
12:00	0.37	0		0	0.93	0.45
13:00	0.35	0		0.26	0.90	0.44
14:00	0.30	0		0.49	0.82	0.42
15:00	0.22	0		0.70	0.68	0.38
16:00	0.12	0		0.85	0.51	0.31
17:00	0	0	0	0.95	0.30	0.20
18:00	0	0	0.14	0.99	0.08	0.05

*Calculated from existing weather conditions.

Theoretical calculations

The dimensionless quantities given in Table 3 are needed to carry out the theoretical calculations.

The calculations from the model are compared with the measured values in Fig. 3. The agreement is remarkably close. It may be that under different sky conditions the model does not work quite as well. A more complete investigation and test of the model will be undertaken as a project onto itself.

ANNUAL ENERGY CONSUMPTION

Conditions of the calculation

The annual energy consumption calculations were carried out using a 9-year average weather data file for Austin, Texas (Latitude 31 °N). The south exposure of the structure was considered to be made of an opaque wall with the following characteristics:

Conductance = 0.1 Btu h^{-1} ft^{-2} $°F^{-1}$ =
= 5.27 W m^{-2} $°C^{-1}$

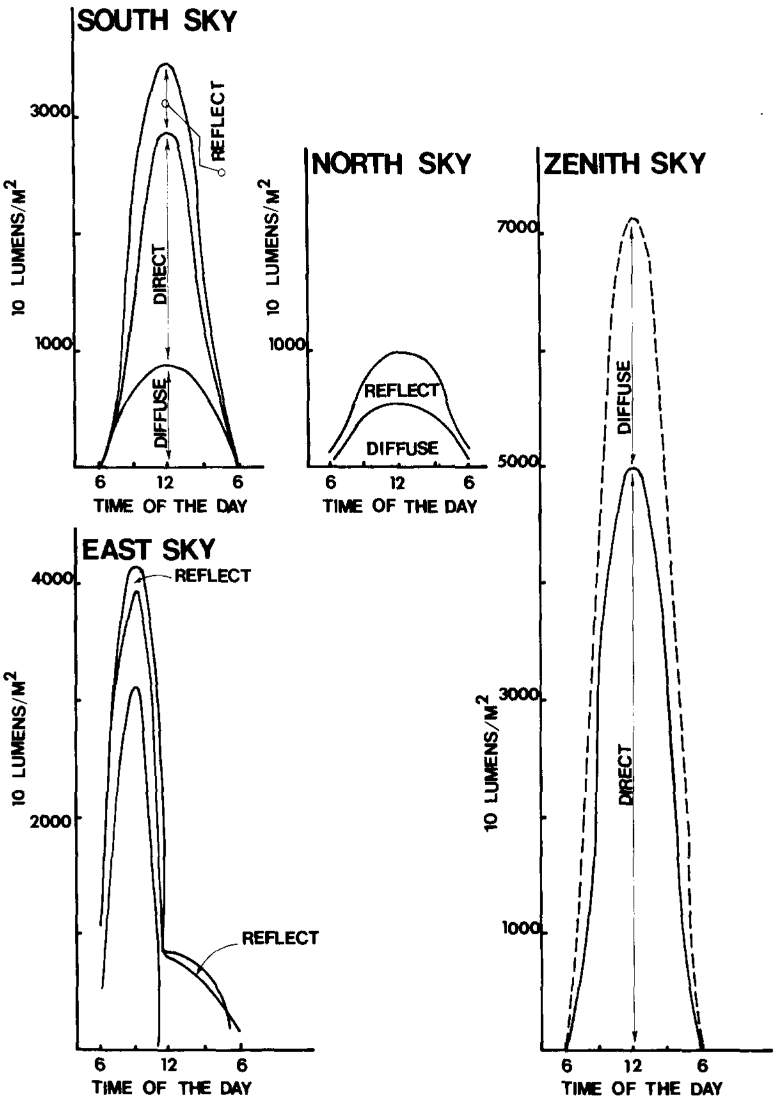

Fig. 3. Comparison of the empirical sky illumination values for various times of the day for various sections of the sky with the values predicted by the sky illumination model used in this article. The tallest curve represents the total illumination. It results from adding the direct and diffuse values. The zenith sky readings were taken from a horizontal plane. The south, north, and east sky readings were taken from a vertical plane oriented in the corresponding directions.

Thermal inertia index (γ) = 2.2

$$\gamma = \sqrt{\frac{\rho c w}{2k}}L$$

where ρ is the density (lb./ft^3); c the specific heat (Btu lb^{-1} °F^{-1}), k the conductivity (Btu h^{-1} ft^{-2} °F^{-1}), L the thickness (ft), and w the frequency (diurnal cycle = 2 π/24 hours). Visible absorptance = 0.5, infrared absorptance = 0.92 and surface roughness = 2 on a scale from 1 to 4 from smooth to rough.

The windows are made of heat absorbing glass; they are shaded from direct sunlight from March to September. The spaces are occupied from 8:00 a.m. to 5:00 p.m. During occupancy the lighting level is required to have a constant value of 30 lumens/ft^2; and the thermostat is set at 78 °F for cooling and 68 °F for heating. During the unoccupied hours the lighting is turned off and the thermostat is set back to 85 °F for cooling and 55 °F for heating.

The artificial light fixtures are assumed to have a maintenance factor of 0.8 and a utilitarian factor of also 0.8 and a luminous efficiency of 20 lumens/watt. The inside walls are assumed to have a reflectance of 0.4. The only external wall of the room is facing true south.

All other surfaces of the room are internal and are assumed to have no thermal conductance.

Other than the heat generated by electric lighting, no internal heat generation is assumed to exist. Air infiltration takes place at the rate of two volume changes an hour; and forced ventilation is also taken to have the same value. The surface to volume ratio of the structure varies from 0.05 ft^{-1} to 0.3 ft^{-1} in steps of 0.05 ft^{-1}; and the fraction of glass on the wall is from zero to forty percent in steps of 5%.

Calculation of room illumination

The intensity of the illumination is calculated at 9 points on the floor of the room. Windows are considered as extended sources of diffuse radiation. Direct sunlight is considered only as it is reflected from an internal surface, and then that section of the wall reflecting the light is also treated as an extended source. The calculation includes the complete series of multiple diffuse reflections and transmissions. Although the program can accommodate specular reflections, this mode was not used in these calculations. The position of the windows on the wall was chosen so as to obtain the most uniform illumination distribution on the floor. This was done by calculating the total sky factor for each window area and surface to volume ratio of the room. Only the external surface wall (south wall) is considered in calculating the surface to volume ratio so that this ratio becomes the inverse of the room depth for a rectangular room. For each value of surface to volume and percent of window the position of the window was changed throughout the wall. The total sky factor was calculated (program RUMLITE) as each of the nine points on the floor, and so was the average sky factor and the mean square deviation. The window position that yielded the lowest mean square deviation was adopted for the calculations in this article.

Results of the calculations

As the window area increases relative to the wall area several trade offs begin to occur. First, and most obvious, is that the reliance on artificial lighting starts to decrease, and so does that component of the total energy consumption. In addition we also have the fact that the rate of internal heat generation starts going down. This internal heat generation that comes from electric lighting can be desirable whenever the reduction in heating cost during the winter is greater than the increase in cooling costs during the summer. (Sometimes the rate of internal heat generation may be sufficiently great to introduce cooling demands even in winter time. The mechanical equipment model used in this article did not assume the economizer cycle.) Thus depending on the specific conditions of the problem, increasing the window size may result in a decrease of energy consumption for heating and cooling. See Fig. 4 for example. In this case (surface to volume ratio of 0.1) the energy consumption for heating and cooling goes down at first as the window area increases. The reduction comes from a lowering of the cooling cost due mainly to the reduction of internal heat generation, and to a lesser extent to the increase ability of the building skin to release this heat through the increasing glass area.

In this example, therefore, increasing the window area reduces the energy consumption via a tandem effect of reducing electric lighting consumption and reducing cooling costs to remove the internal heat generated by the electric lighting. Further increase in the window area starts increasing the air conditioning cost, and to a slower rate the heating cost, with a net rapid increase in the energy consumption for heating and cooling.

The total energy consumption for heating, cooling, and lighting shows a well defined optimum amount of window area at about 25% of the total wall area.

As the surface to volume ratio of the structure changes the total energy consumption dependence on window area changes, particularly the value of window area for which minimum energy consumption occurs. Figure 5 shows the total yearly energy consumption (heating, cooling and lighting) as a function of percent glass on the wall parametric on the surface to volume ratio.

This Figure shows the presence of the optimum window area for all values of the surface to volume ratio of the structure; however, as the surface to volume ratio increases (e.g. as the building gets smaller) the optimum window area occurs at smaller percentages of the total wall area.

Figure 5 also indicates the existence of an optimum surface to volume ratio for a given

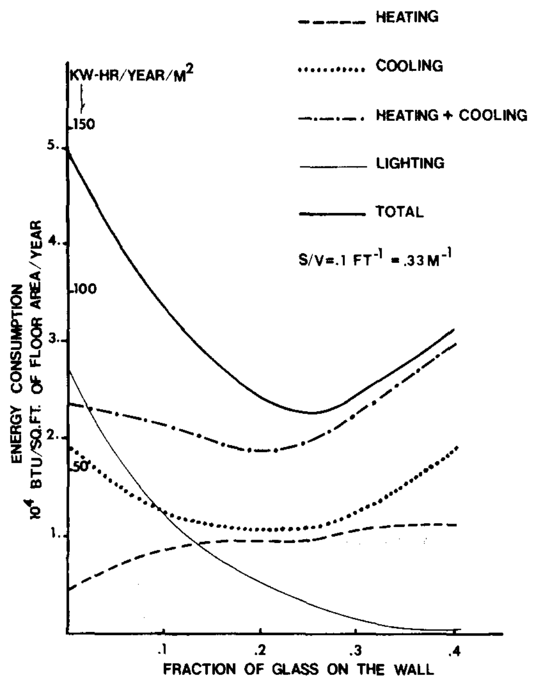

Fig. 4. Annual energy consumption for heating, cooling, and lighting per unit area of floor as a function of amount of window on the wall for a south facing room with surface to volume ratio of 0.1 ft^{-1}. The total energy consumption shows a well defined minimum when the window area is 25% of the wall area. The windows are shaded from direct sun from March through September.

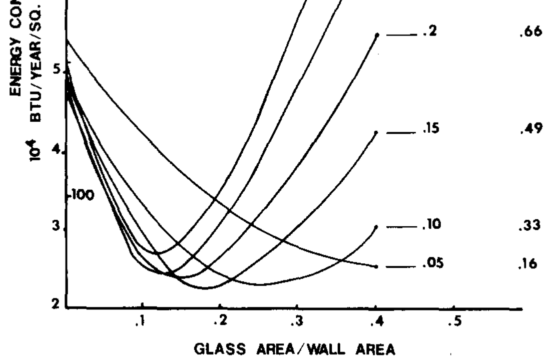

Fig. 5. Annual energy consumption for heating, cooling, and lighting as a function of glass area to wall area ratio parametric on the surface to volume ratio of the space. The figure illustrates the dependence of the optimum glass area on the surface to volume ratio.

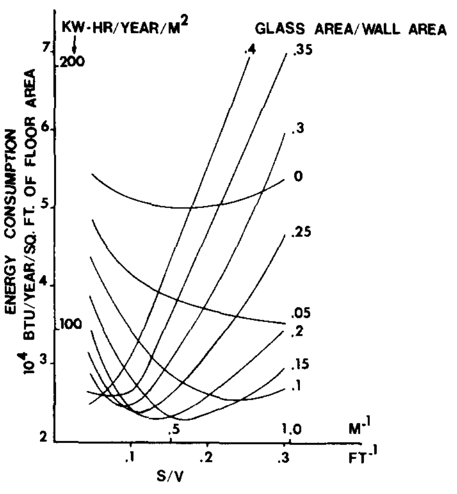

Fig. 6. Annual energy consumption for heating, cooling, and lighting as a function of surface to volume ratio parametric on the relative window area.

window area to wall area ratio. This dependence is shown explicitely in Fig. 6. For the case of walls with 40% window area the energy consumption shows the expected increase as the surface to volume ratio increases; otherwise it shows the existence of an optimum surface to volume ratio, including the case with no windows. This last effect is symptomatic of the presence of internal heat generation; because as the surface to volume ratio increases, the surface through which the heat can be dissipated increases, thus reducing at first the load on the mechanical equipment. For other values of window area the existence of an optimum surface to volume ratio is due to varying combinations of reduced artificial lighting and improved dissipation of internal heat. The existence of minimum energy consumption both as a function of window area to wall area ratio, and as a function to surface to volume ratio suggests the possibility of using contours of constant energy consumption as a possible design aid. Such contours are depicted in Fig. 7. For the example shown here we can even identify an absolute minimum occurring at a surface to volume ratio value of 0.15 ft^{-1} and window area to wall area ratio of 0.18.

Clearly, even in the simplified case studied here we have a relatively complex parametric dependence of the energy consumption as we change the amount of glass in a structure. To help visualize the overall dependence we can construct a 3-D diagram showing the energy consumption as a function of both the surface

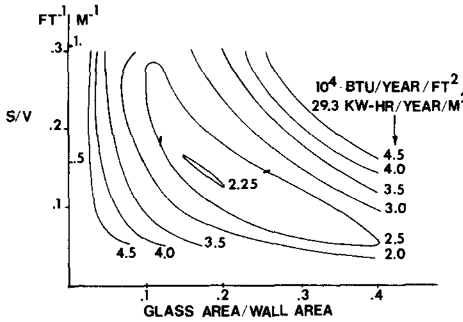

Fig. 7. Contour of constant total energy cost on the plane defined by the surface to volume ratio and the relative glass area.

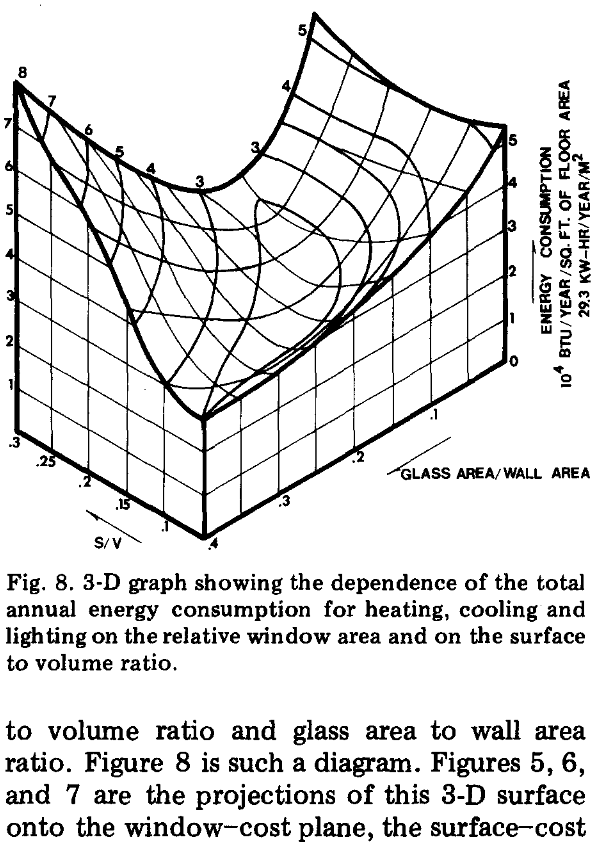

Fig. 8. 3-D graph showing the dependence of the total annual energy consumption for heating, cooling and lighting on the relative window area and on the surface to volume ratio.

to volume ratio and glass area to wall area ratio. Figure 8 is such a diagram. Figures 5, 6, and 7 are the projections of this 3-D surface onto the window–cost plane, the surface–cost plane and the window–surface plane respectively.

CONCLUSION

This article demonstrates the theoretical existence of optimum window areas in buildings which result in significant (50%) energy consumption savings for heating, cooling and lighting. The results indicate that this optimum is a sensitive function of geometry (surface to volume ratio) and window to wall area. These conclusions are strongly dependent on the validity of the sky illumination model used in the calculation; therefore, the article describes in detail the sky illumination algorithm used in these calculations, as well as the empirical test of the mode. Although the preliminary tests of the sky illumination model are encouraging, additional testing must be carried out before more conclusive statements can be made.

These results indicate the existence of real possibility that the careful integration of daylighting with artificial lighting and with building geometry can reduce the total energy consumption in buildings, and it shows a way in which it could be done.

REFERENCES

1 R. G. Hopkinson, *Architectural Physics, Lighting,* Her Majesty's Stationary Office, London, 1963.
2 J. W. Walsh, *The Science of Day Light,* McDonald New York, 1961.
3 H. Nakamura and M. Oki, *Measurement of Luminance Distribution Under Various Sky Conditions by Orthographic Projection Camera.* Publication CIE NO. 36 (1976) Comp. Rendu 18a Session, London, 1975.
4 S. Selkowitz and A. Rosenfeld, Beam and Diffuse Daylighting and Peak, Power, in D. K. Ross (ed.), *Proc. The Basis for Effective Management of Lighting Energy Symposium*, FEA, 1975.
5 J. A. Duffie and W. A. Beckman, *Solar Energy Thermal Processes,* Wiley, New York, 1974.
6 A. D. Meinel and M. J. Meinel, *Applied Solar Energy*, Addison Wesley, 1976.
7 J. D. Sellers, *Physical Climatology,* The University of Chicago Press, Chicago, Ill., 1965.
8 D. M. Gates, *Energy Exchange in the Biosphere,* Harper, New York, 1964.
9 F. A. Brooks, *An introduction to Physical Climatology*, Davis, 1959, as reported by D. M. Gates, *Ibid.*, p. 52.
10 B. Y. H. Liu and R. C. Jordan, as reported by J. A. Duffie and W. A. Beckman, *ibid.*, p. 67.
11 G. I. Pokrowski, *Phys. Z.*, *30* (1929) 697.